# *Announcements*

- EXAM 3 will be *this* Thursday!
- Homework for tomorrow…

  Ch. 34: CQ 8 & 10, Probs. 26 & 58

  CQ8: a) left to right b) zero c) right to left

  33.30: $2.6 \times 10^{-4}$ V

  33.34: $8.6 \times 10^{-4}$ A

- Office hours…

  MW 10-11 am

  TR 9-10 am

  F 12-1 pm

- Tutorial Learning Center (TLC) hours:

  MTWR 8-6 pm

  F 8-11 am, 2-5 pm

  Su 1-5 pm

# Chapter 34

## Electromagnetic Fields & Waves

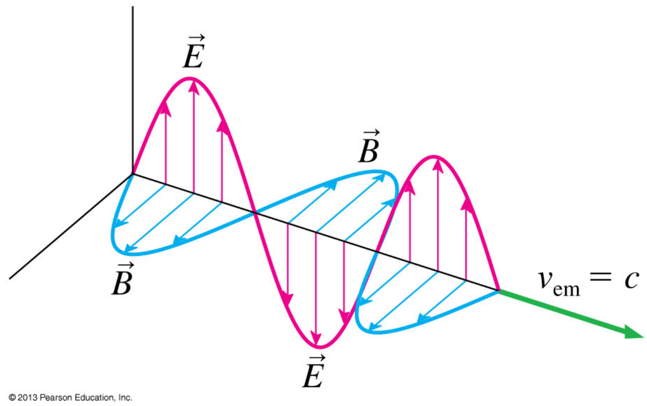
*(Properties of EM Waves & Polarization)*

# *Last time…*

The EM wave a*mplitudes* are related by…

$$\boxed{E_0 = cB_0}$$

The EM wave *speed*, in vacuum, is…




$$\boxed{v_{em} = \frac{1}{\sqrt{\epsilon_0 \mu_0}} \simeq 3.0 \times 10^8 \text{ m/s}}$$

The Poynting vector *is*…

$$\boxed{\vec{S} \equiv \frac{1}{\mu_0} \vec{E} \times \vec{B}}$$

# Energy & Intensity

- The Poynting vector is a function of time, oscillating from 0 to $S_{max}$ and back to 0 *twice* during each period of the wave's oscillation.
- Of more interest is the *average* energy transfer, averaged over one cycle of oscillation, which is the wave's *intensity*.
- The *intensity* of the *EM* wave is…

# Energy & Intensity

- The Poynting vector is a function of time, oscillating from 0 to $S_{\text{max}}$ and back to 0 *twice* during each period of the wave's oscillation.
- Of more interest is the *average* energy transfer, averaged over one cycle of oscillation, which is the wave's *intensity*.
- The *intensity* of the *EM* wave is…

$$\boxed{I = \frac{P}{A} = \frac{1}{2c\mu_0}E_0^2 = \frac{1}{2}c\epsilon_0 E_0^2}$$

# Energy & Intensity

- The *intensity* of a wave fall off with distance.

- If a *point source* with power $P_{source}$ emits *EM* waves *uniformly* in all directions, the *EM* wave intensity at distance *r* from the source is

$$\boxed{I = \frac{P_{source}}{4\pi r^2}}$$

# *Quiz Question 1*

To *double* the intensity of an EM wave, you should increase the amplitude of the electric field by a factor of

1. 0.5.
2. 0.707.
3. 1.414.
4. 2.
5. 4.

# i.e. 34.4: Fields of a cell phone

A digital cell phone broadcasts a 0.60 W signal at a frequency of 1.9 GHz.

What are the amplitudes of the *E*- and *B*-fields at a distance of 10 cm, about the distance to the center of the user's brain?

$I = \langle S \rangle = \frac{1}{2} \epsilon_0 c E_0^2$ $\quad P = 0.60\,W$ $\quad ; \quad I = \frac{P}{4\pi r^2} = \frac{0.60}{4\pi(0.1\,m)^2} = 4.8\,W/m^2$

$\sqrt{\frac{2I}{\epsilon_0 c}} = E_0$

$E_0 = 60\,V/m$ $\quad E_0 = c B_0$

$B_0 = 2.0 \times 10^{-7}\,T$

$E_0 = 60\,V/m$

$B_0 = 2.0 \times 10^{-7}\,T$

# *Radiation Pressure…*

EM waves transfer not only *energy* but also *momentum*.

- Suppose we shine a beam of light on an object that *completely absorbs* the light energy.
- The *radiation pressure* on the surface is…

Radiation Pressure

Moment change from absorbed energy

$$\Delta p = \frac{E}{c}$$

Momentum

The radiation force is

$$F = \frac{\Delta P}{\Delta t} = \frac{E}{c\Delta t} = \frac{P}{c}$$ Power

The radiation pressure

$$P_{Rad} = \frac{F}{A} = \frac{P}{Ac} = \frac{I}{c}$$

# *Radiation Pressure…*

EM waves transfer not only *energy* but also *momentum*.

- Suppose we shine a beam of light on an object that *completely absorbs* the light energy.
- The *radiation pressure* on the surface is…

$$\boxed{p_{rad} = \frac{I}{c}}$$

where $I$ is the *intensity* of the light wave.

Notice: $p_{rad}$ is *radiation pressure* NOT *momentum*!

# i.e. 34.5: Solar Sailing

A low-cost way of sending spacecraft to other planets would be to use the radiation pressure on a solar sail. The intensity of the sun's EM radiation at distances near earth's orbit is about 1300 W/m².

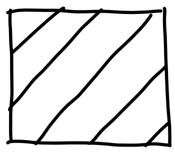
What size sail would be needed to accelerate a 10,000 kg spacecraft toward Mars at 0.010 m/s²?

$P = 1300\ W/m^2$ $\quad M = 10{,}000\ kg$ $\quad a = 0.010\ m/s^2$

$F_{net} = ma$

$= 10{,}000\,kg\,(0.010\,m/s^2)$

$F_n = 100N$



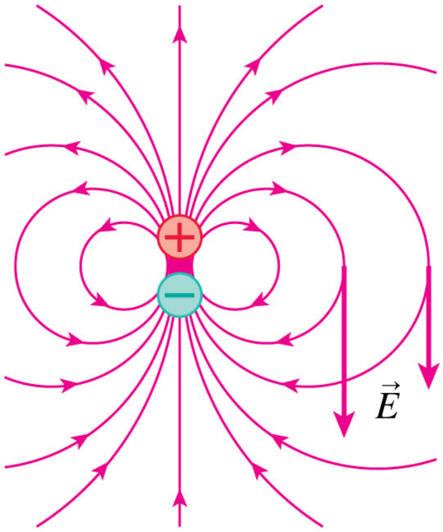
$P = \frac{F}{A} = \frac{I}{c}$ $\quad A = \frac{Fc}{I}$

$A = 2.3 \times 10^7 m^2$ $\quad l^2 = 2.3 \times 10^7 m^2$

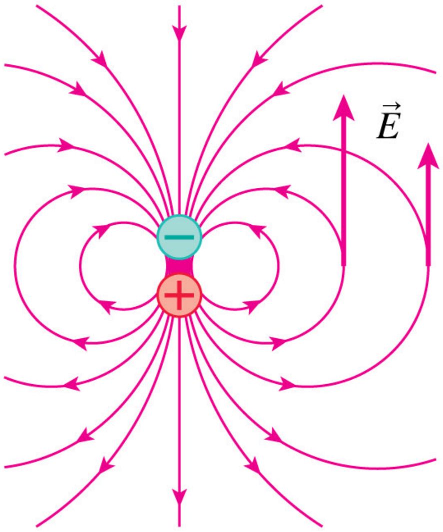
$l = 4{,}800m$

# *Antennas…*

- An electric dipole creates an *E*-field that *reverses direction* if the dipole charges are switched.
  - An oscillating dipole can *generate* an EM wave.

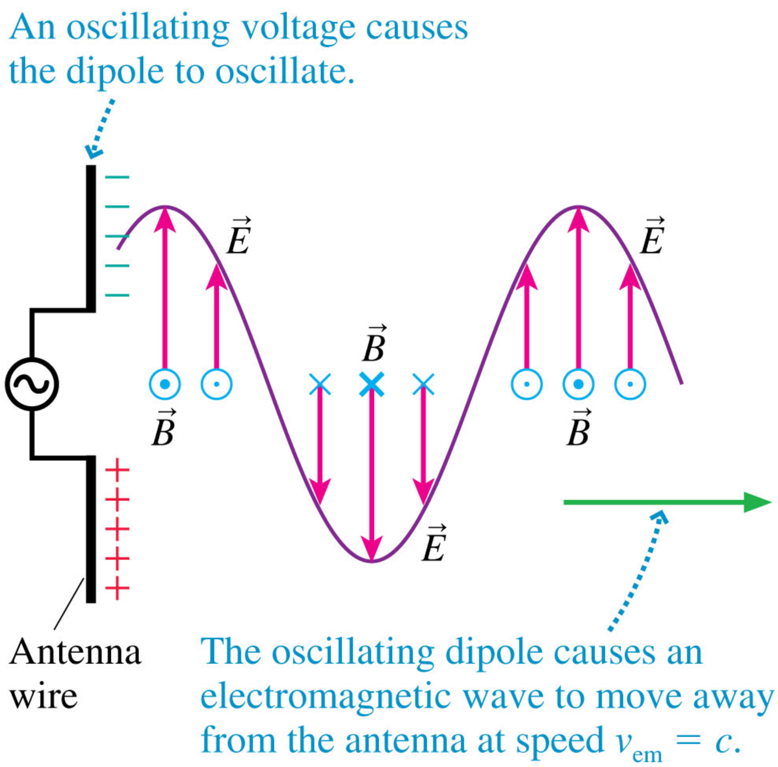



Positive charge on top




Negative charge on top

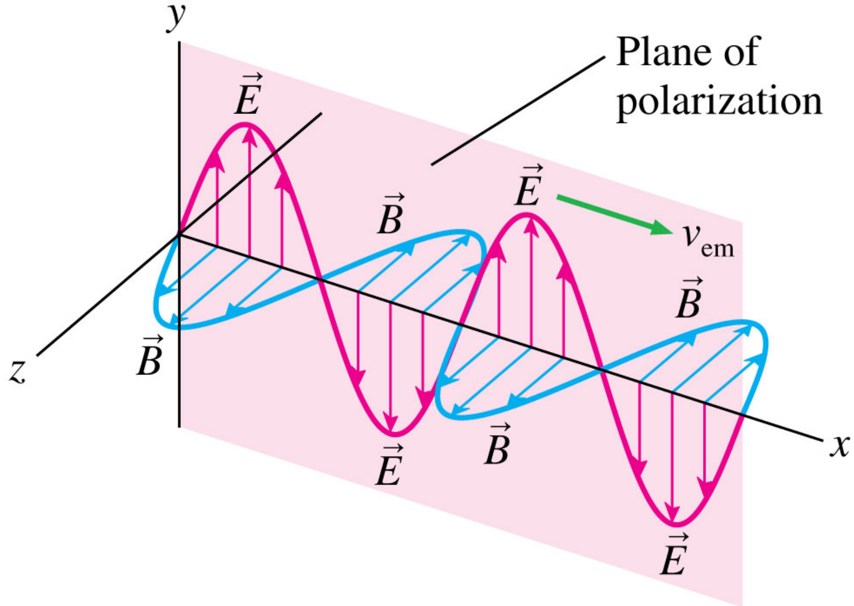
# *Antennas…*




- An antenna acts like an *oscillating electric dipole*, involving both moving charge and a current.
- A self-sustaining EM wave is produced!

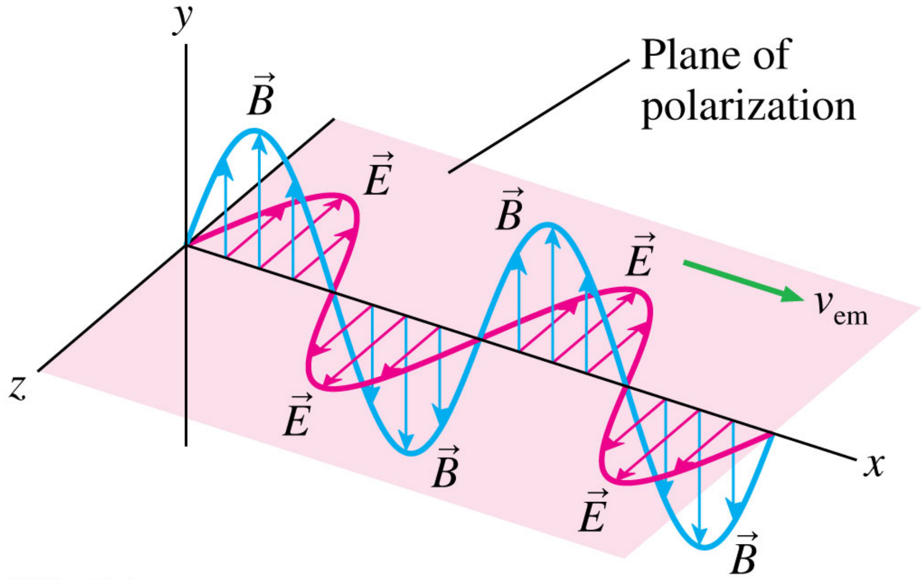
# 34.7: Polarization

- The plane of the *E*-field vector & the Poynting vector, *S*, is called the *plane of polarization*.
- The *E*-field in the figure below oscillates vertically, so this wave is *vertically polarized*.



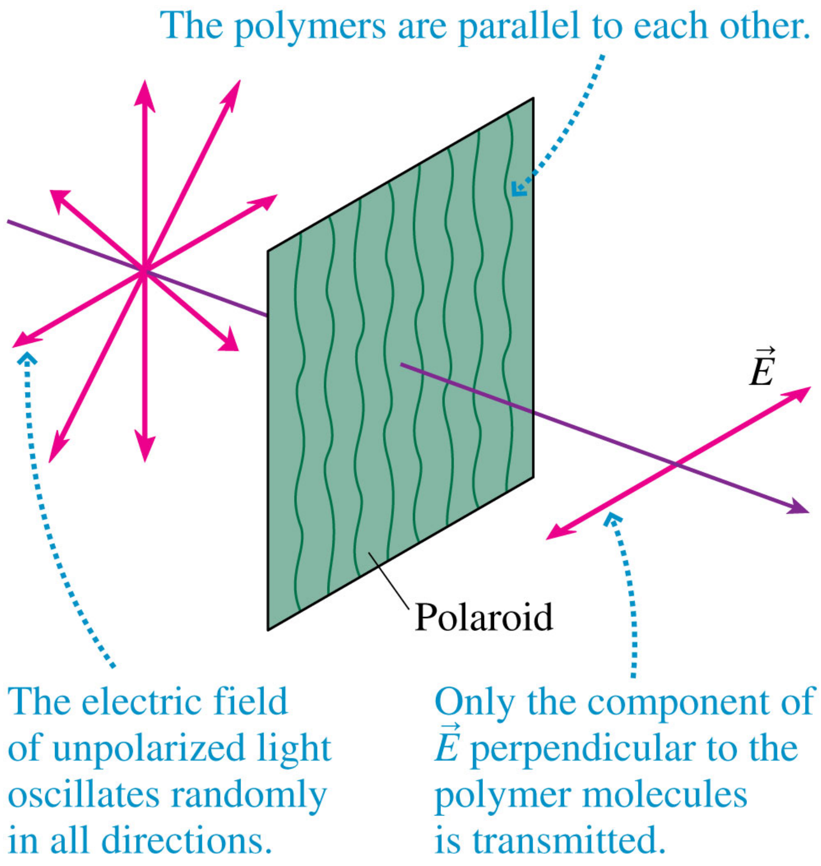
# 34.7: Polarization

The *E*-field in the figure below is *horizontally polarized*…




- Most natural sources of light are *unpolarized*, emitting waves whose *E*-fields oscillate *randomly* with ALL possible orientations.

# 34.7: Polarization



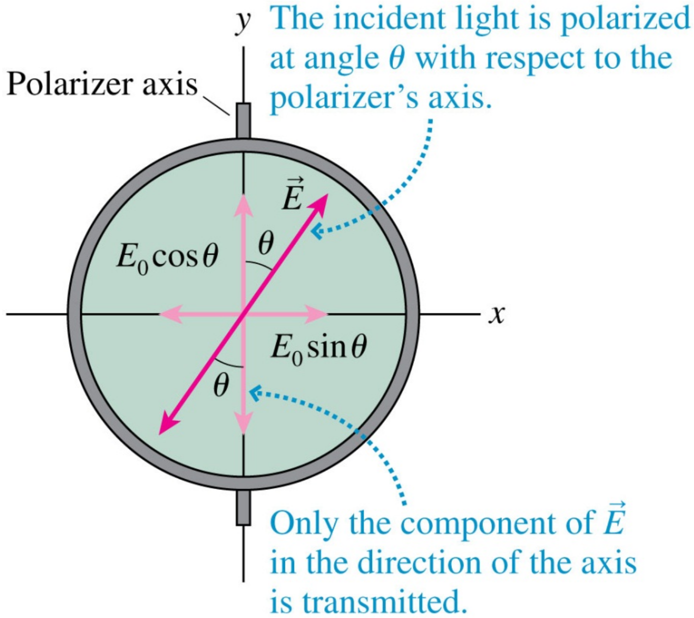

To *polarize unpolarized light*, send it through a *polarizing filter*.

# Malus's Law

Consider *polarized* light of intensity $I_0$ approaching a *polarizing filter*...

The component of the *E*-field that is polarized *parallel* to the axis is *transmitted*.

- The *transmitted intensity* is...



# Malus's Law

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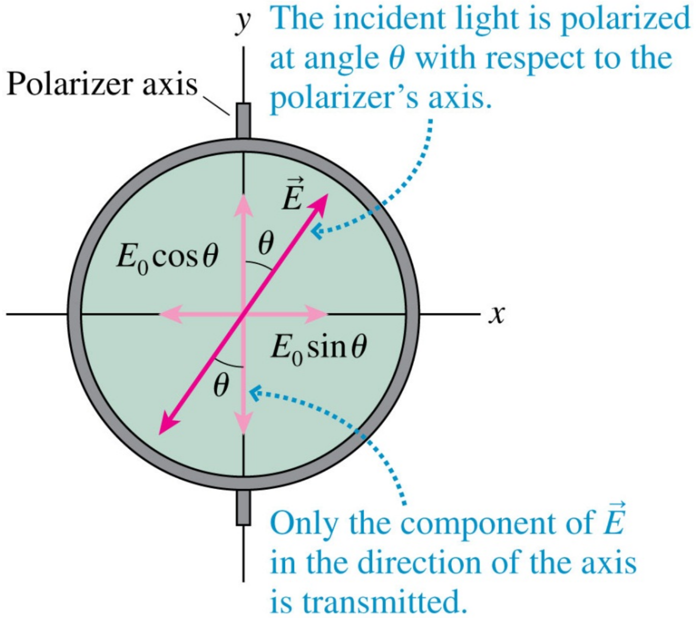
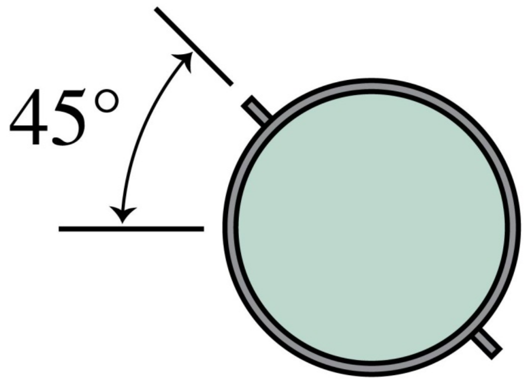
$$I_{trans} = I_0 \cos^2 \theta$$



# *Quiz Question 2*

A vertically polarized light wave of intensity 1000 mW/m² is coming toward you, out of the screen. After passing through this polarizing filter, the wave's intensity is

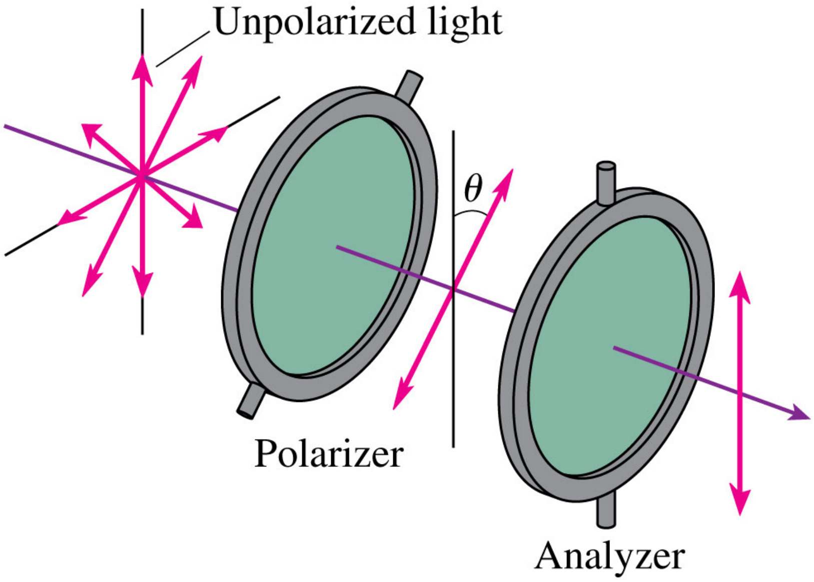



1. 707 mW/m².
2. 500 mW/m².
3. 333 mW/m².
4. 250 mW/m².
5. 0 mW/m².

# *Polarizers and Analyzers…*

Malus's law can be demonstrated with two polarizing filters…

- The first, called the *polarizer*, is used to produce polarized light of intensity $I_o$.




The second, called the *analyzer*, is rotated by angle $\theta$ relative to the polarizer.